Final Report for AOARD Grant 094017

"**Development of nano-slit for high-resolution detection of atoms with near-field lights**"

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Abstract: We made a slit-shaped structure with the width of 50 nm working as an atom detector. We estimated from finite difference time domain simulations that the radius of curvature of less than 32 nm was required as the machining accuracy of the edge for detecting cold Rb atoms.

Introduction: Near-field light overcoming the diffraction limit can be applied to atomic-level deposition. Actually, we have developed an atom deflector using a repulsive dipole force from near-field light [1,2]. In the first demonstration, we used the two-step photoionization with a diode laser beam and an Ar-ion laser beam to detect deflected Rb atoms. However, since the spatial resolution was very low, about 100 μm, we were not able to check the diffraction pattern in detail. The atom detection system with high spatial accuracy exceeding 100 nm is essential to near-field optical manipulation of atoms. Unfortunately, there is no commercial detector with a resolution over 10 μm to our knowledge. To this end, we develop an atom detector required for atom-manipulation experiments with near-field light.

Figure 1 shows the detection scheme using a nanometric-wide slit, where we illuminate the slit with evanescent light produced by total-internal reflection. In this case, scattering light that decreases the spatial resolution is suppressed [3]. Two-color near-field lights generated on the nano-slit ionize atoms by two-step photoionization. The ionized atoms are counted with a channel electron multiplier (CEM). The spatial resolution is approximately equal to the slit width. We obtain the spatial distribution of atoms by moving the slit detector with a nano-actuator. Figure 2 shows the relevant energy levels for detecting Rb atoms. Near-field light generated from a laser diode (LD) with a wavelength of 780 nm excites Rb atoms from the $5S_{1/2}$ ground state to the $5P_{3/2}$ excited state, and then near-field light generated from a Ar^+ laser with a wavelength of 476.5 nm excites them across the ionization level.

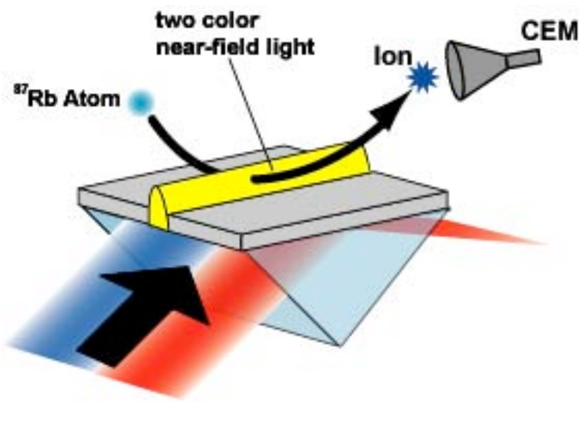

Fig. 1 Sketch of detecting atoms.

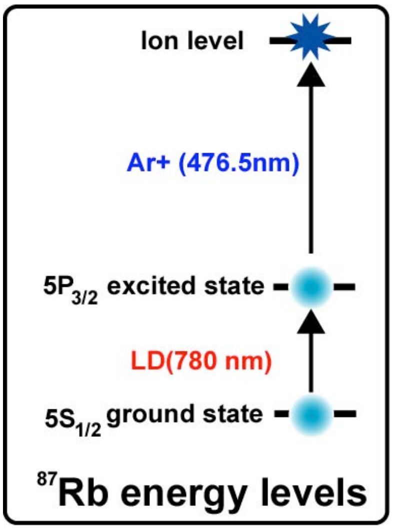

Fig. 2 Relevant energy levels of two-step photoionization of Rb.

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14. ABSTRACT
The researchers made a slit-shaped structure with the width of 50 nm working as an atom detector. We estimated from finite difference time domain simulations that the radius of curvature of less than 32 nm was required as the machining accuracy of the edge for detecting cold Rb atoms.

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References:
1. K. Totsuka, H. Ito, K. Suzuki, K. Yamamoto, T. Yatsui, M. Ohtsu, “A slit-type atom deflector with near-field light,” Appl. Phys. Lett. Vol. 82, No. 10, 1616-1618, 2003.
2. K. Yamamoto, K. Totsuka, H. Ito, “Deflecting atoms through a submicron-sized slit with near-field light” Optical Review, Vol. 13, No. 5, 357-360, 2006.
3. T. Sato, H. Ito, “Sub-100-nm-wide slit for detecting ground state atoms with near-field photoionization,” J. Nanophoton. Vol. 1, 011560, 2007.

Fabrication: The detector device has the structure shown in Fig. 3. A slit is formed by FIB milling of an Al layer on a SiO_2 glass plate. Figure 4 shows the SEM image. The width, the height, and the length of the slit is 50 nm, 50 nm, and 10 μm, respectively.

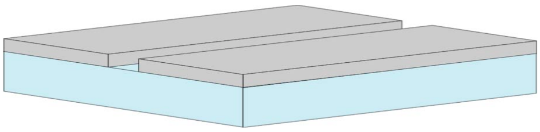


Fig. 3 Structure of the detector device

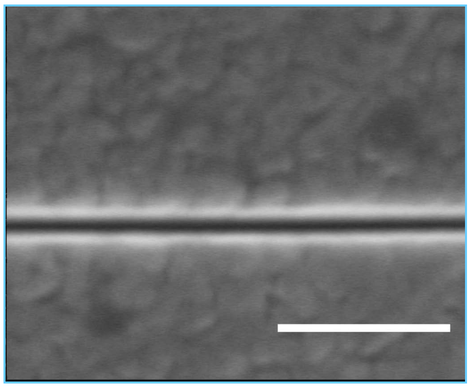


Fig. 4 SEM image of the top view of the slit

Simulations: Scattering light arises in associate with generation of near-field light. It is important to suppress scattering light that deadly decreases the spatial resolution. We numerically examined how scattering light is emitted in generating near-field light on a 50-nm-wide slit using finite difference time domain (FDTD) method. When the slit was illuminated with evanescent light produced by total-internal reflection of an s-polarized beam introduced in the longitudinal direction of the slit as shown in Fig. 5, the intensity of scattering light was suppressed down to 10^{-7} compared to that of near-field light. The intensity profile of near-field light has double peaks in the scattering-less configuration if each edge of the slit is sufficiently steep. However, as the edges get out of shape, the double-peak structure is lost and the peak-intensity becomes lower. Consequently, the ionization efficiency of atoms decreases. This time, we examined the intensity profile of near-field light produced on the nano-slit as a function of the radius of curvature of the edge by conducting FDTD simulations.

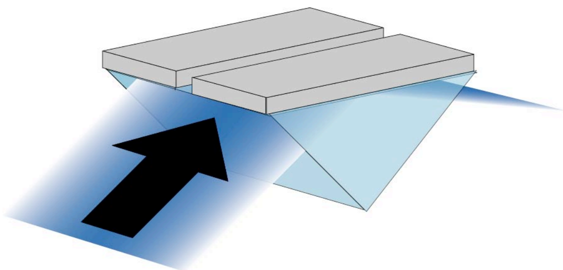


Fig. 5 Scattering-less scheme of generating near-field light on a slit.

Figure 6 shows the cross section of the 50-nm-wide slit with the height of 50 nm. The ionization efficiency greatly depends on the near-field light intensity with 476.5 nm since the cross section of the ionization from the $5P_{3/2}$ state is very low. Therefore, we calculated the intensity profile in the case where the incident intensity of the Ar^+ laser beam is 10 W/cm^2, changing the polarization and the radius of curvature of the slit edge.

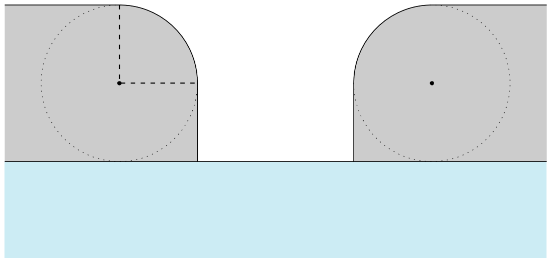


Fig. 6 Configuration of FDTD si,ulations

Results and Discussion: Intense near-field light produced from the Ar^{+} laser beam with the wavelength of 476.5 nm is required for ionizing Rb atoms. Figure 7 shows near-field light in the cross section when the 50-nm-wide aluminum slit is illuminated with the 476.5-nm evanescent light. As shown in the upper figure, if the edge is square, the intensity becomes double peaks. On the other hand, as shown in the lower figure, when the radius of curvature is 50 nm, the double-peak structure is lost and near-field light is drawn into the slit.

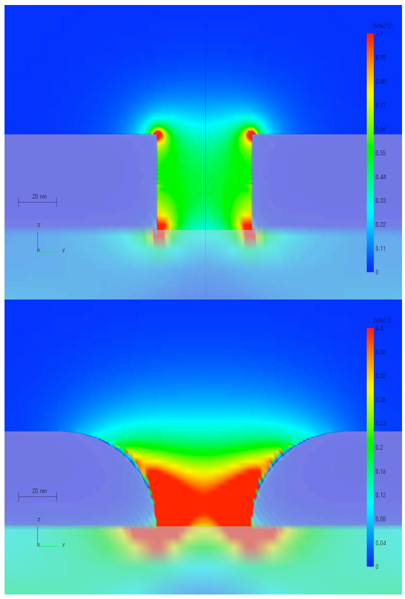
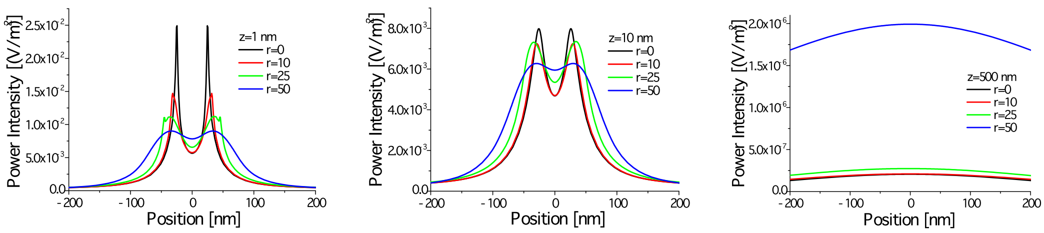


Fig.7 Cross-sectional intensity distributions in the slit. The upper figure shows the case of the square edge, while the lower figure shows the case where the radius of curvature is 50 nm.

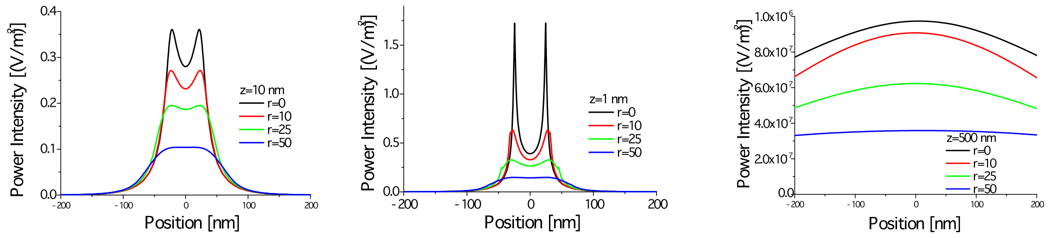
Figure 8 shows the case of the p-polarization illumination, where the intensity profile is calculated at (a) 1 nm, (b) 10 nm, and (c) 500 nm, from the upper surface of the slit. In the vicinity of the surface, as the radius of curvature (*r*) is larger, the peak intensity is lower.



(a) (b) (c)

Fig.8 Intensity profile in the s-polarization illumination.

Figure 9 shows the case of the s-polarization illumination, where the intensity profile is calculated at (a) 1 nm, (b) 10 nm, and (c) 500 nm, from the upper surface of the slit. The intensity of near-field light produced on the slit is much stronger than that obtained in the p-polarization illumination. In addition, scattering light is well suppressed as shown in (c).



(a) (b) (c)

Fig.9 Intensity profile in the p-polarization illumination.

We estimated the ionization efficiency given by

$$\mu[\phi_0] = 1 - \exp[-\frac{\sigma_{ion}\phi_0 L}{2v}]$$

in the scattering-less configuration, where σ_{ion}=2X10^{-17} cm^2 is the cross section of ionization for the Rb atom in the 5P3/2 state, ϕ_0=7.7X10^{26} s^{-1}cm^{-2} is the incident photon flux intensity, L=90 nm is the decay length, and v=10 cm is the incident speed of the Rb atoms. In the experiment, we will use cold Rb atoms generated by a magneto-optical trap. We also assumed the beam waist of 80 μm. Figure 10 shows the result plotted as the function of the radius of curvature. When the radius of curvature is 32 nm, the ionization efficiency is 0.1. The detection efficiency is given by the quantum efficiency of CEM, which is 0.9 if the negative bias of -3 kV is applied.

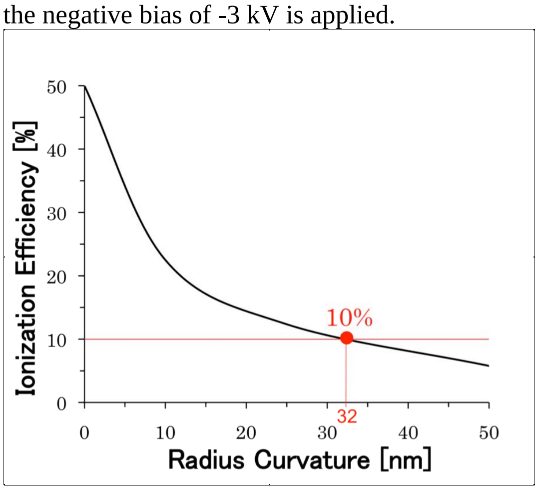


Fig. 10 Ionization efficiency of slow Rb atoms with the 50-nm-wide slit.

In conclusion, the sharp edge with the radius of curvature of less than 30 nm is required for high-efficient detection of cold Rb atoms using the 50-nm-wide slit.

Unfortunately, the high-power Ar$^+$ laser was broken in the beginning of the demonstration experiment. It took a long time to change with a new laser tube, which is very expensive exceeding this grant. Consequently, we was not able to conduct the demonstration experiment. We want to perform it near future.

The nano-slit device we develop in this research will be applied to experiments of deflecting and nano-focusing atoms with nanometric near-field lights and open up doors to nanofabrication in atomic scale and development of nano-photonic/quantum functional devices.

Conference Presentations:

1. T. Sato, H. Ito, “Edge dependence of near-field light generated on a nano-slit,”
   Spring meeting of the Japan Society of Applied Physics, 18a-P4-26, Kanagawa, March 18, 2010.
2. T. Sato, H. Ohki, H. Ito, “Generation of near-field light on a nano-slit for atom detection,”
   11^{th} International Conference on Near-field Optics, Nanophotonics & Related Techniques,
   Beijing, August 29-September 2, 2010.